PB90-103060

# Air Cleaner Technologies for Indoor Air Pollution

Research Triangle Inst., Research Triangle Park, NC

Prepared for:
Environmental Protection Agency, Research Triangle Park, NC

1988

U.S. Department of Commerce
National Technical Information Service
NTIS

AEERL-P-413

**TECHNICAL REPORT DATA**
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| | | |
|---|---|---|
| 1. REPORT NO. EPA/600/J-88/387 | 2. | 3. RE PB90-103060 |
| 4. TITLE AND SUBTITLE Air Cleaner Technologies for Indoor Air Pollution | | 5. REPORT DATE<br>6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S) D. S. Ensor, A. S. Viner, J. T. Hanley, P. A. Lawless, K. Ramanathan, M. K. Owen, T. Yamamoto (RTI); and L. E. Sparks | | 8. PERFORMING ORGANIZATION REPORT NO. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Research Triangle Institute<br>P. O. Box 12194<br>Research Triangle Park, North Carolina 27709 | | 10. PROGRAM ELEMENT NO.<br>11. CONTRACT/GRANT NO. CR814169-01 |
| 12. SPONSORING AGENCY NAME AND ADDRESS<br>**EPA, Office of Research and Development**<br>**Air and Energy Engineering Research Laboratory**<br>**Research Triangle Park, NC 27711** | | 13. TYPE OF REPORT AND PERIOD COVERED Journal article; 10/87-5/88<br>14. SPONSORING AGENCY CODE **EPA/600/13** |

15. SUPPLEMENTARY NOTES AEERL project officer is Leslie E. Sparks, Mail Drop 54, 919/541-2458. Published in ASHRAE Journal, Engineering Solutions to Indoor Air Problems, pp. 111-129 (1988); Proceedings of IAQ 88, Atlanta, GA, 4/11-13/88.

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17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Pollution | Pollution Control | 13B |
| Air Cleaners | Stationary Sources | 13A |
| Condensing | Indoor Air | 07D |
| Measurement | | 14G |
| Mathematical Models | | 12A |
| Ozone | | 07B |
| Organic Compounds | | 07C |

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

| | | |
|---|---|---|
| 18. DISTRIBUTION STATEMENT **Release to Public** | 19. SECURITY CLASS *(This Report)* **Unclassified** | 21. NO. OF PAGES 22 |
| | 20. SECURITY CLASS *(This page)* **Unclassified** | 22. PRICE |

EPA Form 2220-1 (9-73)

EPA/600/J-88/387

# Air Cleaner Technologies for Indoor Air Pollution

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## ABSTRACT

Air cleaners have been widely used to control both particulate and gaseous pollutants in indoor spaces. The detailed performance of air cleaners is needed for data in a computer-based Indoor Air Quality Simulator being developed. Methodologies for the particle-size-dependent performance measurement of air cleaners are described. The use of laser optical particle counters and condensation nucleus counters with preseparators in evaluating air cleaners is discussed. The selection of a challenge aerosol is particularly important; materials include nebulized dissolved solids in water or low-vapor-pressure organics. Another area of increased attention is the generation of ozone by electronic air cleaners. Ozone production rates from a wire plate electrode configuration are summarized.

Activated carbon adsorbents have been used in commercial air cleaners to remove organic materials. The absorption of low concentrations (below 200 ppb) of materials such as benzene and acetaldehyde obtained in laboratory isotherm experiments is reviewed.

## INTRODUCTION

A new initiative sponsored by the U.S. Environmental Protection Agency (EPA) is the development of a computer-based Indoor Air Quality Simulator (IAQS) that will incorporate emission sources, sinks, ventilation, pollutant interactions, effects, economics, and air-cleaning technologies. The planned applications of this tool include its aiding in the design of indoor spaces for acceptable air quality, interpreting

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experimental results, and allowing policymakers to evaluate scenarios with respect to building practices. A review of the indoor air quality literature indicates that additional, fundamental information on air cleaners is required to support development of the simulator.

A number of fundamental air cleaner performance characteristics are perceived to be important in air quality:

1. Particle-size-dependent removal efficiency. The performance of an air cleaner depends on the particle-size-dependent efficiency and the particle-size distribution of the aerosol. The wide range of potential pollutants demands that this information be available for particles with different physical properties.

2. Behavior of semivolatile particles after collection. Some of the combustion-generated pollutants are condensed hydrocarbons. An episode of these pollutants may load the air cleaner, and the collected material may be subjected to evaporation until the air cleaner is replaced or cleaned.

3. Secondary emissions from air cleaners, such as ozone and particles. Electronic air cleaners can generate ozone (Sutton et al. 1976) and particles (Offermann et al. 1985).

4. The change in performance of collectors with age. As the collector is filled, efficiency could improve, as claimed with fibrous filters, or sorption devices could be degraded.

5. The control of volatile organics at low concentrations. Organic pollutants usually occur in parts per billion concentration levels, and control is required to prevent chronic exposure in indoor spaces. Little information is available on sorbent performance under these conditions.

6. Energy required by air cleaners. The energy required to provide clean air is a measure of the effectiveness of the removal process, and it is a significant factor for economic considerations.

## BACKGROUND

There are three basic approaches to air cleaner evaluation, as suggested by Rivers and Murphy (1986):

1. **Simulate Actual Conditions.** This is the approach recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 1976), but it is difficult to follow because one must simulate the possible conditions of application. The purpose of the ASHRAE tests is to allow specification of air cleaner performance for specific applications. One example of this approach is the use of a test room filled with tobacco smoke, such as described by Offermann et al. (1985), to perform comparative testing of a variety of air cleaners.

2. **Test at an Extreme Condition.** This approach was used in the MIL-STD-282 (U.S. Army Chemical Corps 1956) test of high-efficiency particulate air (HEPA) filters. A nearly monodisperse 0.3 $\mu$m diameter aerosol was selected to match the most penetrating particle diameter through the filter. It is assumed that, if the filter

passes this test, more than adequate protection will be provided when the filter is in service.

3. **Obtain Fundamental Performance Data and Combine with a Model.** This approach was described by Rivers and Engleman (1982) for ventilation systems and also by Ensor et al. (1987) for clean rooms. Woods and Krafthefer (1986) described the potential coupling of the ventilation equations with air cleaner efficiencies to predict indoor air quality. A systematic approach allows focusing on one aspect of the technology at a time. The physical limitations of pollutant removal of a well-characterized material by an air cleaner can be determined by carefully controlled tests. Then its efficiency under realistic conditions of ventilation/mixing and pollutant properties can be predicted by computer simulation and verified by experiment.

It should be pointed out that fundamental performance data can yield quite different results than tests conducted to rate the collector. The properties of the aerosol (such as particle size distribution, phase [liquid or solid], resistivity, and adhesion) have significant influence on the results. For example, Irie et al. (1986) performed in situ measurements of the efficiency of an 85-percent ASHRAE filter with optical particle counters and found a collection efficiency of 14 percent.

Many types of particles are usually found in homes and offices. In both indoor environments, tobacco smoke may be a major particle source. Also, radon progeny, both attached to other aerosol particles and unattached, are important. In addition, biological particles, bacteria, and pollen can be present. Homes can include combustion particles resulting from gas appliances, wood stoves, and fireplaces, as well as particles produced during cooking. Other particles that can be present result from various spray propellent products, such as antiperspirants, paints, hairsprays, and air fresheners. An office environment may often include particles given off by equipment such as copying machines.

Most cigarette smoke particles, both by weight and number, are found in the submicrometer diameter range (Chang et al. 1985; Leaderer et al. 1984).

Owen et al. (1986), in a test of office aerosols, found a number distribution mode of approximately 0.13 $\mu$m diameter, with the number of particles dropping off sharply as the diameter approached 10.0 $\mu$m. The size distribution for radioactive, unattached radon progeny particles is in the 0.01 to 0.05 $\mu$m size range (Ho et al. 1982). Johansson et al. (1983), assuming a log-normal distribution for particles 0.01 to 1 $\mu$m, tested 11 dwellings and determined the area median diameter for attached particles to be approximately 0.2 $\mu$m. Biological particles, bacteria, and pollen are reported in the size range larger than 1.0 $\mu$m (Offermann et al. 1985). Particles from spray products include diameters between 2 and 9 $\mu$m (Mokler et al. 1979). These values indicate that particles throughout the inhalable range, but especially in the submicrometer range, are present in indoor aerosols. Therefore, performance tests of air cleaners should cover the particle diameter range from 0.01 to at least 15 $\mu$m.

Concentrations of indoor air particles vary with ventilation rate, number of occupants, activities, and the influx of outdoor air. Quant et al. (1982) reported average daytime peak concentrations in an office to range from 80 to 110 $\mu g/m^3$ with smokers present and from 50 to 60 $\mu g/m^3$ with no smokers. Owen et al. (1986) reported a comparable concentration range (from 20 to 130 $\mu g/m^3$) in an office building. Repace and Lowrey (1980) reported concentrations above 200 $\mu g/m^3$ (and as high as 675 $\mu g/m^3$ for one sports arena) for areas with smoking.

## PARTICLE AIR CLEANERS

There are two main types of indoor air cleaners: in-duct and room cleaners. In-duct cleaners are installed within heating, ventilating, and air-conditioning (HVAC) systems. Room air cleaners contain a filter and perhaps an absorber with a self-contained fan. The control approach used in both cases includes fibrous filtration, electrostatic precipitation, and electrostatically augmented filtration. Vapors are usually adsorbed by activated carbon. A more complete description of the hardware may be found in *ASHRAE Equipment* (ASHRAE 1983).

The performance measurement of in-duct air cleaners is the focus of this paper. Room air cleaners are usually tested in chambers rather than in instrumented test ducts (Offermann et al. 1985; Whitby et al. 1983). Also, particle emission source strengths can be determined in chambers under the proper experimental conditions (Donovan et al. 1987).

### Performance Measurement of In-Duct Air Cleaners

The components of a filter test apparatus include an aerosol generator, a test filter holder, and particle detection instruments. The development of testing methodology requires matching the aerosol generation technique to the instrumentation and obtaining the desired filter data. For example, if a polydisperse test aerosol is used, an instrument capable of high-resolution particle size distribution measurements is required for the upstream and downstream measurements. If a monodisperse aerosol is used, the particle size (once determined) does not need to be measured during the filter efficiency test. In addition, simple particle concentration detection instruments can be used with monodisperse particles. Because of the need to test only the media or the entire filter assembly, additional trade-offs that affect the design of the test fixture may be required. The time needed to test the assembly is an important consideration. In an industrial quality control test, only a limited amount of time is available; whereas, more time and care can be taken in a research setting to obtain a wider range of data with additional replication.

**Standard Test Methods.** Table 1 summarizes the current standard test methods. Except for the hot DOP method, all of the standards use polydisperse aerosols. None of these methods gives particle-size-dependent efficiencies. It should be noted that these test methodologies were developed more than 20 years ago when sensitive particle-measuring instruments and monodisperse particle generators were not available.

The ASHRAE test methods were developed for low-efficiency ventilation system filters. The other methods were developed to test HEPA filters originally developed during World War II. The range of efficiencies of interest in air pollution control falls between these two extremes.

The evaluation of electrostatic air cleaners requires additional considerations, as described by Rivers and Murphy (1986). Conductive test dusts may cause electrical failure or abnormal performance.

**Specialized Test Methods.** A number of filter-testing methodologies have been reported in the literature, and a few are summarized in Table 2. A variety of test aerosols have been used for filter challenges, including aerosol generated by atomization, condensation, sprayed latex microspheres, and resuspension of solid material or the ambient atmosphere. Detectors have included condensation nucleus counters, photometers, electrical charge detectors, and optical particle counters.

Some of the newer approaches have been the use of a laser optical particle counter and dilution of condensation DOP aerosol to test HEPA filters (Scripsick 1986). Remiarz

**TABLE I**
**Summary of Methods for Filter Efficiency Measurement: Standard Tests**

| Method | Aerosol generation and property | | | | | Aerosol detection | | Reference |
|---|---|---|---|---|---|---|---|---|
| | Material | Dispersity | Generation technique | Diameter (MMD) ($\mu$m) | Concentration (mg/m$^3$) | Detector | Penetration measured (%) | |
| 1. DOP Test Hot (U.S. standard) | Dioctyl phthalate | Monodisperse | Vaporization condensation | 0.3 | 100 | Light-scattering photometer | 0.001 and up | ASTM D2986 Standard (1956) MIL-STD-282 (1956) |
| 2. Sodium flame test (British standard) | NaCl | Polydisperse | Atomizing 2% aqueous soln. | 0.6 (0.01-1.7) | — | Flame photometer | 0.001-0.1 | British Standard 3928 (1969) |
| 3. Methylene blue test (British standard) | Methylene blue | Polydisperse | Atomizing 1% aqueous soln. | (0.01-1.5) | — | Stain density | 0.01-50 | British Standard 2831 (1971) |
| 4. Uranine test (French standard) | Uranine | Polydisperse | Atomizing 1% aqueous soln. | 0.3 | 10 | Fluorometer | 0.001 and up | Prudel and Brion (1970) |
| 5. ASHRAE test—Prev. NBS and AFI tests (U.S. standard); includes three parts: | | | | | | | | |
| 1. Weight arrestance: | 72% fine dust 23% Morocco black 5% 7 cotton linters | Polydisperse | AFI dust feeder | — | ~1000 | Gravimetric | 2-80 | ASHRAE Standard 52-76 (1976) |
| 2. Dust spot efficiency | Atmospheric aerosol | Polydisperse | — | ~0.3 | ~0.1 | Opacity meter | 2-80 | ASHRAE Standard 52-76 (1976) |
| 3. Dust holding capacity | Same as 5(1) | Polydisperse | AFI dust feeder | — | ~1000 | Gravimetric | 2-80 | ASHRAE Standard 52-76 (1976) |
| 6. SAE test | AC-fine<br>AC-coarse | Polydisperse<br>Polydisperse | Sonic dust feeder and others | 8<br>32 | ~1000 | Gravimetric | — | SAE J726c (1979) |
| 7. Cold DOP | Dioctyl phthalate | Polydisperse | Nebulizer | 0.7 | 100 | Light-scattering | — | ANSI N101.1 (1972) |

**TABLE 2**
**Summary of Methods for Filter Efficiency Measurement: Standard Tests**

| | Aerosol generation and property | | | | | Aerosol detection | | |
|---|---|---|---|---|---|---|---|---|
| **Method** | **Material** | **Dispersity** | **Generation technique** | **Diameter (MMD) (μm)** | **Concentration ($mg/m^3$)** | **Detector** | **Penetration measured (%)** | **Reference** |
| 1. Monodisperse aerosol-electrical detection | Dioctyl phthalate | Monodisperse | Vaporization condensation | 0.03-1.0 | 100 | Electrical aerosol detector | 0.001 and up | Liu and Lee (1976) |
| 2. Polydisperse aerosol-CN detection | Ambient aerosol | Polydisperse | Ambient | 0.04 nmd | $N = 10^5/cm^3$ | CN counter | 0.1 and up | Appel and Wesolowski (1972) |
| | Gold, silver | Polydisperse | Vapor.-condens. and spray-drying | 0.005-0.03 nmd | $N = 10^7/cm^3$ | CN counter | 0.001 and up | Sinclair (1976) |
| | atomizer | Polydisperse | Vapor.-condens. and spray-drying | 1 and below | N = up to $10^7/cm^3$ | CN Counter | 0.01 and up | Silverman and McGreevy (1967) |
| 3. Monodisperse and polydisperse aerosol-optical detection | Latex spheres | Monodisperse | Spray-drying | 0.09-2 | N = up to $10^4/cm^3$ | Photometer | 0.01 and up | Rimberg (1969); Lindeken et al. (1963) |
| | Ambient aerosol | Polydisperse | Ambient | >0.3 nmd | $N = 10^3/cm^3$ | Optical counter | 0.01 and up | Appel - nd Wesolowski (1972) |
| | PSL, oleic acid, uranine | Both | S-D, V-C, etc. | 1-3 | 0.02-4 | Photometer | 0.01 and up | Shleien et al. (1966) |
| 4. Polydisperse aerosol-fluorometric detection | Uranine | Polydisperse | Atomizer | 0.025-0.27 | — | Flurometric | 0.01 and up | Posner (1961) |
| 5. Airborne radioactivity-alpha detection | Ambient aerosol with decay product | Polydisperse | Ambient | 0.04 nmd (0.001-0.04) | $N = 10^3/cm^3$ | Alpha detector | 1.0 and up | Lindeken (1961) |
| 6. Miscellaneous | NaCl uranine oil, fly ash | Polydisperse | Atomizer and spinning disk | 0.05-6.0 | Varied | Fluorometric, gravimetric, titrametric, atomic absorption, microscopic, etc. | 0.01 and up | Lundgren and Gunderson (1975) |

PSL = Polystyrene latex
CN = Condensation nucleus
N = Number particles/$cm^3$

et al. (1986) described the use of a condensation nucleus counter to test respirator filters challenged with a salt aerosol produced by atomization.

**Testing Precautions.** A few difficulties can be encountered in obtaining particle-size-efficiency data for low-efficiency ventilation filters. At the particle-size range of minimum efficiency, upstream and downstream concentrations may differ as little as 20 percent. Changes in challenge concentrations and size distribution during the test and differences in upstream and downstream instrumental responses may yield artifacts. The errors in optical particle counters (such as coincidence and minimum count statistics) were reviewed by Whitby and Willeke (1967). Liu et al. (1986) reported that laser particle counters have a nonmonotonic particle size response and, therefore, should be used with caution for comparative results. If a pair of optical particle counters is used, care should be taken to match the instruments' response. An alternative is to use a single set of instruments to measure first the upstream and then the downstream concentrations. This approach requires a very stable aerosol generator. In addition, nonuniform aerosol concentration within the duct and sampling biases from nozzle effects (alignment and isokinetic flow) should be considered (Hinds 1982).

## Test Results

Ventilation filters are being tested with an apparatus of original design (see Figure 1). The system has two back-to-back containment filter holders that allow, not only easy access to the back of the media during the test, but also the ability to test a range of combinations of filters. The system is operated at positive pressure (1 cm WG) within a Class 100 clean room to prevent artifacts caused by inleakage when testing filters of ultrahigh efficiency. The system can use the clean room as the source of air when the instruments and the system are checked for background counts.

The two filter holders, which will accept 2 × 2 ft (60 × 60 cm) filters, are constructed of stainless steel, and the system ducting is 8 inch (20 cm) diameter polyvinyl chloride (PVC). Reducing the duct diameter upstream and downstream of the filter test section reduces stratification, and the resulting increase in gas velocity improves accuracy in velocity measurements and particle sampling. The penetrating aerosol sample tap is located sufficiently far downstream of the test filter to allow for the complete mixing of any penetrating aerosol with the entire airstream. By running the downstream ducting back under the filter holders, the challenge and penetrating aerosol taps are located physically near each other, thereby allowing short sample lines and reductions in particle losses. The losses in the ductwork were found to be insignificant for the particle sizes of interest.

Aerosol instrumentation used for the tests consisted of a laser particle counter (LPC) (Knollenberg 1985), an optical particle counter (OPC), and a mobility separator (DMPS) (Keady et al. 1983) with a condensation nucleus counter (CNC) as a detector. The laser counter was used to measure the particles from 0.09 to 3 $\mu$m, the OPC from 0.3 to 3 $\mu$m, and the mobility separator from 0.011 to 0.457 $\mu$m.

Airflow was monitored with a digital thermal anemometer probe placed at the center of the duct. Duct traverses and pitot probe measurements were used to determine the flow rate. The pressure drop of the air cleaner was measured with an inclined manometer.

An aerosol generated by nebulizing solutions of potassium chloride was used as the particle challenge. Nebulizers produce a polydisperse droplet size distribution (mean diameter = 0.4 $\mu$m and a geometric standard deviation of 2). The mean diameter of the dry residue of potassium chloride can be controlled by the strength of the solution and was varied during the test.

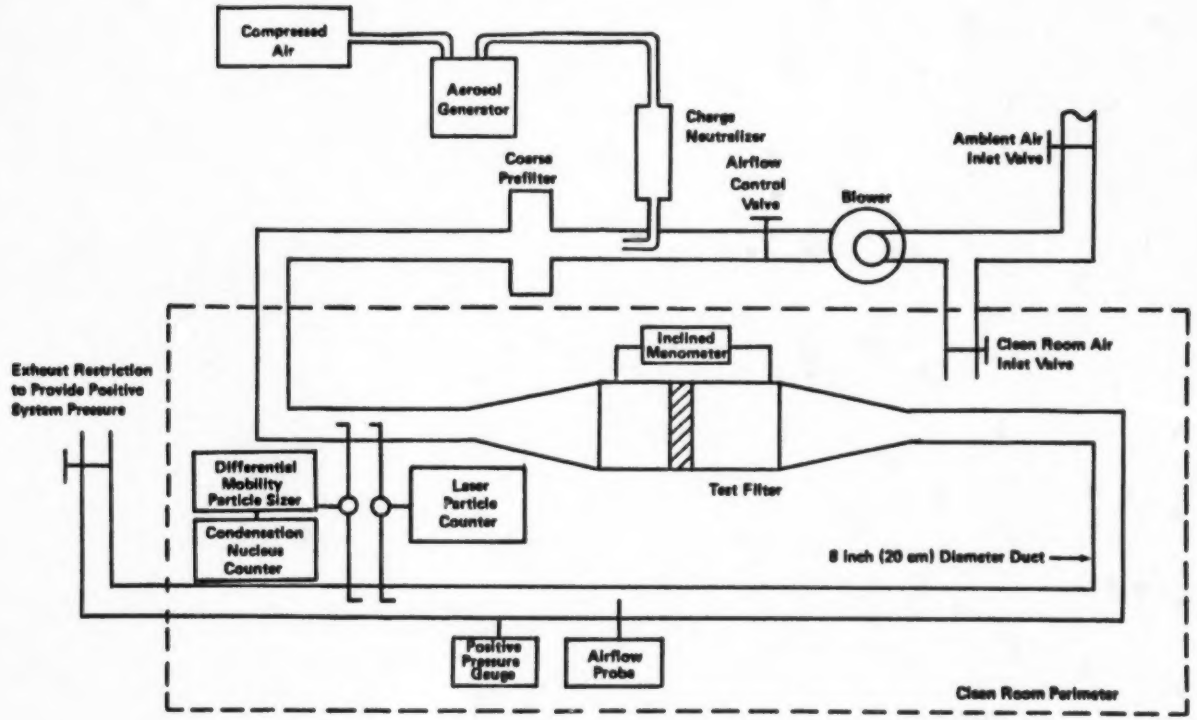


**Figure 1 Schematic diagram of air cleaner testing facility**

An example of an evaluation of several filters (1 × 2 ft [30 × 61 cm]) at the rated flow of 500 acfm (14 $m^3$/min) is shown in Figure 2. Particle efficiency as a function of particle diameter is shown with various arrestance rated filters. The increased efficiency for ultra-small particles is caused by diffusional collection.

## OZONE PRODUCTION

High electron energies, such as those found in electrostatic precipitators, induce a number of chemical reactions in gas molecules surrounding electrodes. This fact was recognized by Thomson (1893), who discovered that these gaseous reactions are fundamental steps inherent in electrical breakdowns rather than incidental side effects. Ozone is one of the products that result from electronic excitation of oxygen.

The hazardous nature of ozone has prompted several studies of ozone generation by electrostatic discharges over the last 50 years. Castle et al. (1969) conducted one of the more rigorous studies by quantifying ozone generation in a cylindrical electrostatic precipitator using positive corona. Their results confirmed the work of White and Cole (1960), which showed that the ozone production rate is proportional to the power input to the electrode. In addition, Castle and his co-workers adapted Townsend's (1914) equation for the critical field strength (i.e., field strength required to produce corona) as a function of wire radius to calculate an average field strength as a function of wire radius. Based on their observations, Castle et al. (1969) developed a model of ozone generation for the cylindrical precipitator geometry:

$$O_3 = K \frac{E_{av}\, a\, I}{Q} \qquad (1)$$

*where*

$O_3$ = ozone concentration, ppb

$K$ = empirical constant

$E_{av}$ = average field strength, *kV*/inch (*kV*/cm)

$a$ = wire diameter, inch (cm)

$I$ = current, mA

$Q$ = airflow, L/s.

Subsequent measurements on a larger precipitator produced good agreement with theory at low currents, but errors of 50 percent or more occurred at higher currents. In later work, Awad and Castle (1975) found that heating the discharge electrode significantly reduced the generation rate. They also found that the production rate was somewhat dependent on the electrode material.

Some design criteria have been developed for indoor air cleaners to reduce the production of ozone (Castle et al. 1969):

1. Use of positive (rather than negative) polarity corona.
2. Use of a two-stage design in which the charging and collection functions are separate.
3. Use of smooth, round corona wire of the smallest possible diameter compatible with mechanical strength.

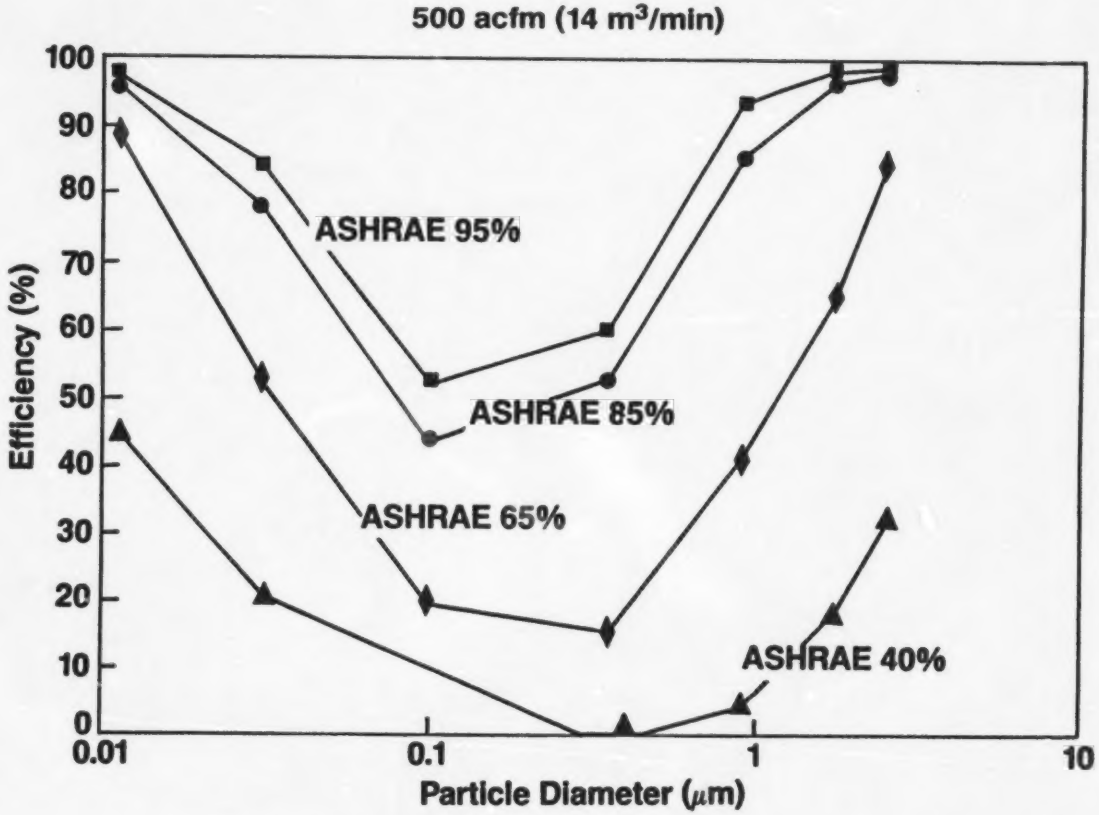


**Figure 2** Particle-size-dependent efficiency for various grades of ventilation filters

4. Use of the lowest possible corona current compatible with satisfactory collection efficiency.
5. Use of the maximum airflow rate compatible with satisfactory collection efficiency.
6. Elimination of stray discharges, such as may occur due to end effects, sharp points, or edges.

In addition, it is known that the ozone concentration in air is influenced by the presence of other molecular species such as hydrocarbons and water vapor. Sutton et al. (1976) reported that ozone concentrations in residential structures with electrostatic air cleaners were expected to be below outdoor air quality limitations. However, the objectives of the IAQS initiative require that this effect of air cleaners be quantified with respect to ozone production under a wide range of conditions. Indoor ozone levels under a wide range of operational conditions may be important for health effects from chronic, low-level exposure as well as to provide a potential for reactions with other pollutants such as hydrocarbons.

For the experimental approach, a versatile test apparatus is in operation that will allow several parameters to be investigated (Figure 3). Variations of wire-and-plate electrode geometries and resulting concentrations of ozone are of high interest. The experimental parameters and variables include: (1) corona polarity and type, (2) wire-and-plate electrodes, (3) wire diameter and composition, (4) plate spacing and location, (5) airflow rate, (6) air temperature, (7) humidity, (8) power input (current and voltage), and (9) ozone concentration.

The test equipment consists of an airtight, transparent plastic chamber containing the electrodes connected to an external direct current (DC) power supply. The incoming air is cleaned with a high-efficiency prefilter. The walls of the chamber are transparent to allow inspection of the corona during the test. The inlet relative humidity can be controlled by mixing saturated air and dry air. The inside of the aluminum transition at the exit of the chamber is lined with inert plastic to reduce surface reactions. Downstream of the reaction chamber is a mixing section followed by an ozone detector as well as flow-measuring, dewpoint temperature measuring, and air temperature measuring instruments.

## Results

In a typical experimental arrangement, a wire-plate geometry is used, and the ozone production rate is measured as a function of power input and humidity. In one test series, a 1/8 inch (3.2 mm) diameter wire was placed midway between 3 inch (7.5 cm) wide parallel plates spaced 4 inches (10 cm) apart. Negative polarity was used to generate a "tuft" corona (i.e., the corona was confined to localized tufts along the length of the wire). Given this arrangement, the data shown in Figure 4 were obtained at a constant low humidity (17 percent relative humidity). The abscissa is the ozone generation rate (the product of the ozone concentration and the flow rate through the ESP), and the ordinate is the power input to the system (the product of the applied voltage and measured corona current). The data shown in Figure 4 reproduce the linear relationship reported earlier by Castle et al. (1969) and other workers. The solid line in Figure 4 is a regression line constrained to pass through the origin. The slope of the regression line is $3.8 \cdot 10^{-3}$ mg/W • s. For comparison, ozone generation from a tabletop room air cleaner was measured and found to have a production rate of $2.8 \cdot 10^{-4}$ mg/W • s. The differences between these two values are largely a result of the differences in geometry

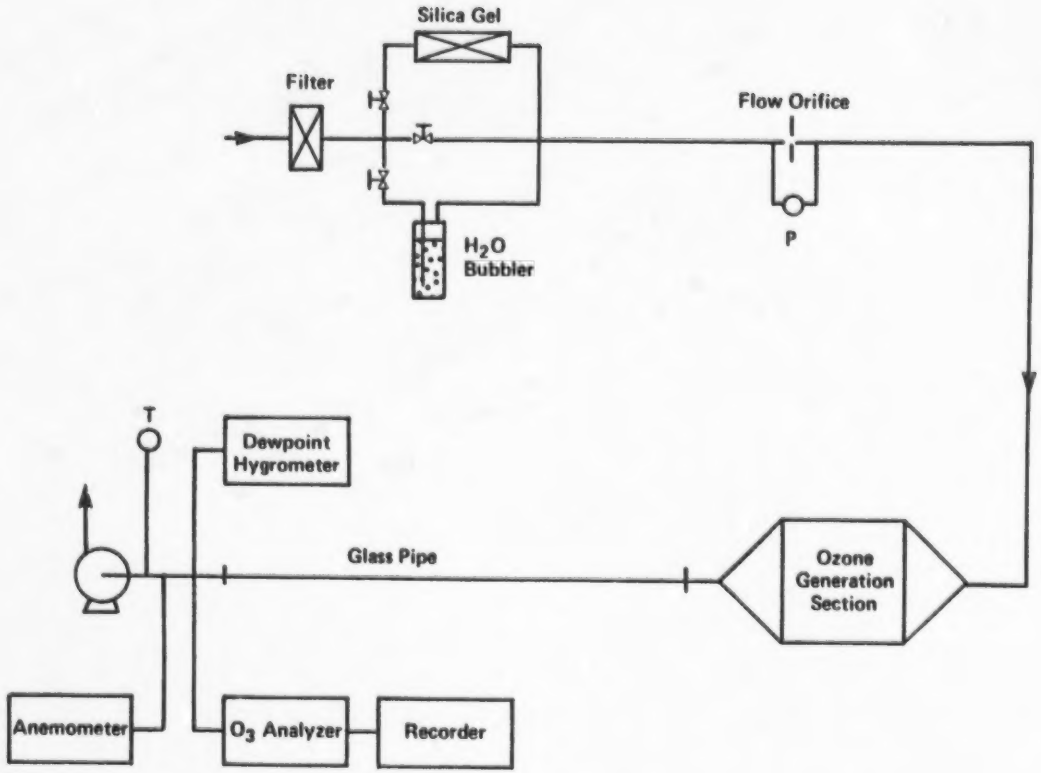


**Figure 3 Ozone generation test apparatus**

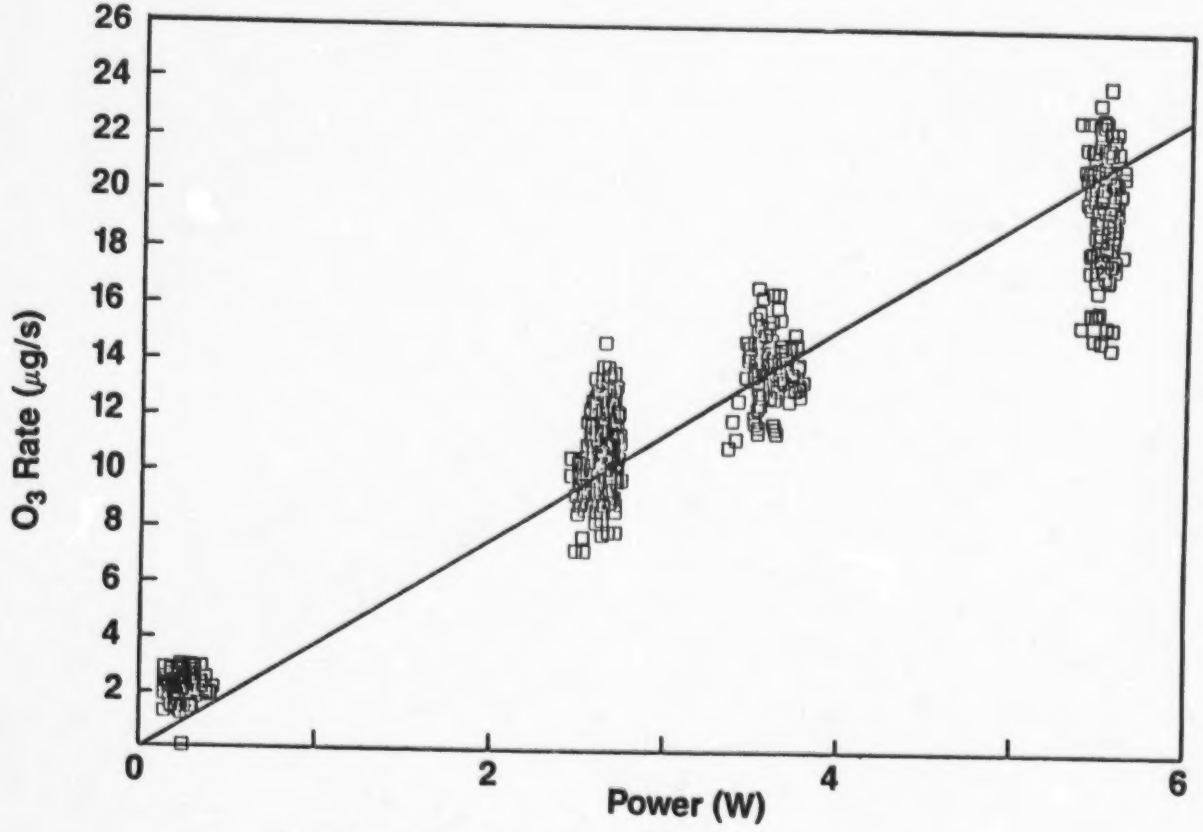


**Figure 4 Ozone generation vs. power input (17% relative humidity)**

(the tabletop air cleaner uses a much smaller wire diameter) and the fact that the tabletop air cleaner uses positive rather than negative corona.

## SORPTION

Controlling volatile organic compounds (VOCs) with air cleaners in indoor environments with sorption is one option requiring evaluation. Often, air cleaners employ filters or electrostatic precipitators in series with a sorption bed for combined pollutant removal. Air cleaners can supplement other measures such as ventilation, material/product selection, material/product use, and other approaches such as bake-out. However, based on work performed to monitor indoor air quality (Wallace et al. 1987; Wang 1975), it appears that these concentrations rarely exceed a few parts per million, and most are often in the few hundred parts per billion range. A variety of organic compounds is found in the indoor environment, and the concentrations of various materials can vary widely. Moreover, the concentrations and species depend on the building being studied.

However, adsorption on activated carbon seems to be the most popular technique currently in use for indoor applications. Some fundamental work was done on adsorption in the sub-10 ppm range with the objective of developing fundamental sorption data under these conditions, predicting performance of activated carbon beds in air cleaners, and ultimately supporting the IAQS development. A detailed description of the work was reported by Ramanathan et al. (1987), and only an overview will be presented here.

### Experimental Method

The adsorption isotherms were measured gravimetrically in the dynamic or flow mode at atmospheric pressure. A microbalance was used to weigh the VOC uptake on carbon (weighing accuracy of $+0.5\ \mu g$). This equipment may be operated under low-temperature, high-vacuum conditions to determine BET surface area. The carbon sample of 150 to 200 mg was degassed under flowing nitrogen while being heated with an infrared lamp until constant weights were obtained over a 15-minute interval. The sample was then allowed to cool in nitrogen before switching to the airstream and introducing the permeation tube to generate a stable concentration of the challenge hydrocarbon. Flow rates were adjusted to give the desired concentrations, and constant weight again was observed.

### Results

Selected results from the experiment are shown in Table 3. The capacities (mol/g carbon) do not vary much with either compound or carbon in the concentration range studied. The capacities ranged from $10^{-3}$ to $10^{-4}$ mol/g. Acetaldehyde uptake is about two to three times lower than that of the other compounds studied.

The isotherm data developed in this study were used to estimate the size of adsorber required to control VOCs at the parts per billion levels observed in an indoor environment. An engineering design equation (Kohl and Riesenfeld 1979) was used to compute bed depths, and the results are summarized in Table 4. It was assumed that the challenge was 150 ppb of benzene, and the superficial velocity of gas across the filter was assumed to be 12.7 cm/s, corresponding to a flow of 100 cfm (283 Lpm) across a 2 × 2 ft (61 × 61 cm) filter. An exit concentration of 50 ppb was set as the level corresponding to a useful bed life. Breakthrough occurs rather quickly, which indicates that a very deep bed is required to provide a reasonable lifetime. This is a conservative estimate because toxicological data are not available for the concentrations. The control of low levels of

**TABLE 3**
**Summary of Adsorption Results**

| Compound | | Uptake[a] | |
|---|---|---|---|
| Acetaldehyde | AC-35 | GAC 410G | Barneby Cheney |
| Concentration (ppb) | mol $CH_3CHO$/g C | mol $CH_3CHO$/g C | mol $CH_3CHO$/g C |
| 119 | 3.39E-07 | 3.52E-07 | 1.99E-06 |
| 153 | 4.17E-07 | 1.00E-06 | 1.00E-06 |
| Benzene | AC-35 | GAC 410G | Barneby Cheney |
| Concentration (ppb) | mol $C_6H_6$/g C | mol $C_6H_6$/g C | mol $C_6H_6$/g C |
| 101 | 2.42E-07 | 1.24E-07 | 4.30E-07 |
| 119 | 4.30E-07 | 6.37E-07 | 5.60E-07 |
| 176 | 1.00E-07 | 7.27E-07 | 6.33E-07 |
| 1,1,1-Trichloroethane | AC-35 | GAC 410G | Barneby Cheney |
| Concentration (ppb) | mol $CH_3CCl_3$/g C | mol $CH_3CCl_3$/g C | mol $CH_3CCl_3$/g C |
| 115 | 7.49E-08 | 1.15E-07 | 2.04E-07 |
| 183 | 1.33E-07 | 2.80E-07 | 1.91E-07 |

[a] Each number represents the average of three to four data points.

VOCs appears to be difficult with conventional carbon adsorption technology, but it may be viable in cases of short-term, high concentrations found during releases, which push the concentration into regimes where the shape of the isotherm is more favorable and sufficient driving force exists for a reasonable uptake. Additional work is planned on full-scale absorbers to confirm this observation.

## SUMMARY

Air cleaners are important for improving air quality in indoor spaces. However, some of the detailed performance aspects are currently unknown. A program to determine particle-size-dependent efficiency, carbon sorption for parts per billion concentrations of pollutants, and secondary effects is underway. The information will be used in a data base as part of the IAQS as well for its own scientific merit.

The efficiency of 40 percent ASHRAE ventilation filters for 0.1 to 1 $\mu$m particles is less than 10 percent. However, diffusional collection increases the efficiency to about 50 percent for 0.01 $\mu$m particles.

The generation of ozone in an electrostatic air cleaner is related to the power input and the wire diameter. The electrode design is very important.

**TABLE 4**
**Variation of Exit Concentration of Benzene with Bed Depth[a]**

| $T$ = 4320 $h$ (6 mo) | | $T$ = 30 $h$ | |
|---|---|---|---|
| Bed depth (ft)[b] | Exit Concentration (ppb) | Bed depth, (ft)[b] | Exit Concentration (ppb) |
| 1098.4 | 121 | 7.65 | 114 |
| 1097.67 | 115 | 8.15 | 55.6 |
| 1108.95 | 99.5 | 8.31 | 35.1 |
| 1137.29 | 67.2 | 8.41 | 20 |
| 1163.09 | 40.6 | | |

[a] 150 ppb challenge concentration, 25 ft/min (12.7 cm/s) superficial velocity, 0.12 inch (3.0 mm) particle size, and Barneby Cheney type ac carbon.

[b] 1 ft = 0.3048 m.

Control of parts per billion levels of VOCs with activated carbon, based on fundamental isotherm measurements, is believed to be difficult because of the low concentration driving forces. Work is pianned on full-scale absorbers to confirm this observation.

## ACKNOWLEDGMENT

This research is supported by U.S. Environmental Protection Agency Cooperative Agreement CR-814169-01-0.

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## DISCUSSION

**M. Klein**, NIOSH, Cincinnati, OH: This work is quite useful, but I would like to see particle range across entire respirable range at least on selected sampling of filters. Also, was the data repeatable? What are the effects over time? Right now, I am recommending changes of filters based on pressure drop, but I'm not sure this is a very good recommendation. Also, based on the author's data, I cannot recommend recirculation of plant air on systems using those type filters. I have one case where an organization wants to recirculate air from a firing range. Finally, will the author define efficiency in his paper?

**D.S. Ensor:** The present data was limited to particles less than 3 $\mu$m because of the difficulty of accurately sampling large particles. However, it is planned to develop an experimental approach for efficiencies at particle sizes greater than 3 $\mu$m in the future. The ability to reproduce size specific efficiency measurements was very good and within 10%; however, at the present time, several filters with the same ASHRAE rating have not been compared. The present tests were conducted with clean filters, and care was taken not to load the filter with the challenge. Future work is planned to measure changes in performance as filters load.

Efficiency is defined by the following equation:

$$E(d)\% = 100\left[\frac{C_f(d) - C_o(d)}{C_f(d)}\right]$$

*where*

$E(d)$ = collection efficiency for particle of diameter $d$

$C_f(d)$ = concentration of particle of diameter $d$ entering the filter

$C_o(d)$ = concentration of particle of diameter $d$ at the outlet of the filter

**C.J. Weschler**, Bellcore, Red Bank, NJ: For those particle size ranges where the methods overlap, how does the laser particle counter compare with the optical particle counter?

**Ensor:** The white light optical particle counter and the laser particle counter gave comparable efficiency measurement results because the measurement is, in effect, a ratio of inlet and outlet concentration.